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Distribution and relative abundance of humpback whales in relation to environmental variables in coastal British Columbia and adjacent waters

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ABSTRACT

Humpback whales are common in feeding areas off British Columbia (BC) from spring to fall, and are widely distributed along the coast. Climate change and the increase in population size of North Pacific humpback whales may lead to increased anthropogenic impact and require a better understanding of species–habitat relationships. We investigated the distribution and relative abundance of humpback whales in relation to environmental variables and processes in BC waters using GIS and generalized additive models (GAMs). Six non-systematic cetacean surveys were conducted between 2004 and 2006. Whale encounter rates and environmental variables (oceanographic and remote sensing data) were recorded along transects divided into 4 km segments. A combined 3-year model and individual year models (two surveys each) were fitted with the mgcv R package. Model selection was based primarily on GCV scores. The explained deviance of our models ranged from 39% for the 3-year model to 76% for the 2004 model. Humpback whales were strongly associated with latitude and bathymetric features, including depth, slope and distance to the 100-m isobath. Distance to sea-surface-temperature fronts and salinity (climatology) were also constantly selected by the models. The shapes of smooth functions estimated for variables based on chlorophyll concentration or net primary productivity with different temporal resolutions and time lags were not consistent, even though higher numbers of whales seemed to be associated with higher primary productivity for some models. These and other selected explanatory variables may reflect areas of higher biological productivity that favor top predators. Our study confirms the presence of at least three important regions for humpback whales along the BC coast: south Dixon Entrance, middle and southwestern Hecate Strait and the area between La Perouse Bank and the southern edge of Juan de Fuca Canyon.

1. Introduction

Humpback whales (*Megaptera novaeangliae*) in the eastern North Pacific feed from California to western Alaska (Perry et al., 1990). They are common off British Columbia (BC) from spring to fall and are widely distributed along the coast (Ford et al., 2010; Gregr et al., 2000; Williams and Thomas, 2007).

Until recently, most of what was known about humpback whales in coastal BC originated from whaling records. Humpback whales, as well as sperm (*Physeter macrocephalus*), fin (*Balaenoptera physalus*), sei (*Balaenoptera borealis*) and blue (*Balaenoptera musculus*) whales were intensively hunted during commercial whaling, between 1908 and 1967 (Gregr et al., 2000; Nichol and Heise, 1992). Additional information obtained mainly through photo-identification studies have shown movements and migratory destinations and provided estimates of abundance (Calambokidis et al., 2008; Darling et al., 1996; Ford et al., 2009; Rambeau, 2008; Urbán-Ramirez et al., 2000). The Canadian Department of Fisheries and Oceans (DFO) maintains a catalog of humpback whales seen in BC waters containing over 2000 individuals photographed between 1989 and 2006. In recent years, systematic line transect surveys have also been conducted to estimate cetacean abundance, including humpback whales, in inshore BC waters (Williams and Thomas, 2007).

Concerns about the effect of climate change (IPCC, 2007) on the recovery of North Pacific humpback whales (Calambokidis and Barlow, 2004; Calambokidis et al., 2008) cannot be properly addressed without a better understanding of species–habitat relationships. Unfortunately, such studies on humpback whales and their habitat are still rare in most regions, including the feeding grounds of the eastern North Pacific. Humpback whales seem to be associated with bathymetry in the Bering Sea (Moore et al., 2002) and off northern Washington coast, where they also

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prefer relatively colder waters in comparison to other offshore species found in the area (Calambokidis et al., 2004). In the northern California Current System, sea surface temperature (SST), depth and distance to the alongshore upwelling front were the most important variables in a multiple logistic regression model for humpback whales during late spring 2000 and sea surface salinity, latitude and depth were the most important predictors during summer of the same year (Tynan et al., 2005). Depth and distance, SST and fluorescence in the top 50 m of the nearest Aleutian pass resulted in the most significant correlations with humpback whale occurrence along the Aleutian Islands in 2000 and 2001 (Sinclair et al., 2005). Nevertheless, additional habitat modeling studies involving multi-year surveys and a wide range of explanatory variables are necessary to identify what oceanographic processes influence the distribution of humpback whales.

Gregr and Trites (2001) produced predictive habitat models for five whale species, including humpback whales, in BC coastal waters, using whaling records for the period 1948–1967 and six predictor variables (month, depth, slope, depth class and climatologies of sea surface temperature and salinity). Their humpback whale models showed low correlation coefficients due to either small sample size or because of relatively weak association with the predictor variables. However, their annual model confirmed strong association of humpback whales with coastal waters (Gregr and Trites, 2001). Inferences of predictive habitat models are limited to the range of data (e.g. Hamazaki, 2002; Redfern et al., 2006), so habitat models based on contemporary data are necessary to make inferences about the present distribution and habitat use of humpback whales in BC waters. This is vital for providing scientific advice towards identifying critical habitat of humpback whales under DFO guidelines.

The currents and ocean structure along the BC coast, particularly in the semi-protected northern shelf region, are shaped by deep-sea processes, tides, winds and estuarine processes (Thomson, 1981). Therefore, waters with coastal, offshore or mixed properties may be found in the region, resulting in a dynamic oceanographic environment. In light of this, it is desirable to implement habitat models that include not only fixed physiographic variables, but also other potentially important predictors, such as primary productivity and proximity to eddies and fronts, at different spatial and temporal scales.

We sought to investigate the distribution and relative abundance of humpback whales in BC waters in relation to a range of environmental variables, including oceanographic and remote sensing data, using Geographic Information System (GIS) and generalized additive models (GAMs). We hypothesize that the higher densities of humpback whales will be positively correlated with areas of enhanced biological productivity through physical forcing.

2. Material and methods

2.1. Data collection

2.1.1. Surveys

Data on cetacean distribution were obtained during six ship surveys conducted between 2004 and 2006 off the coast of British Columbia, including the waters of Queen Charlotte Sound, Hecate Strait and Dixon Entrance, and the offshore waters on the west coast of the Queen Charlotte Islands, Vancouver Island and Washington State (Fig. 1). Five surveys were conducted during spring and fall months aboard vessels from the Department of Fisheries and Oceans (DFO), Canada (Ford et al., 2010). The first three of these surveys were part of the 'Structure of Populations,

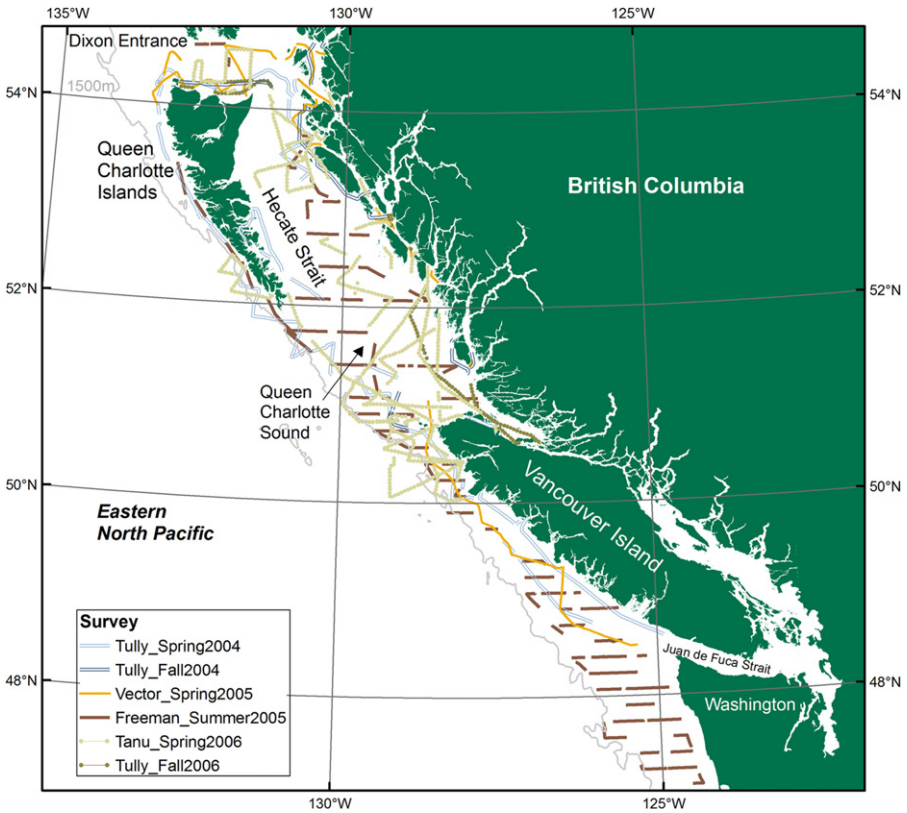

Fig. 1. Cetacean surveys conducted off the coast of British Columbia between 2004 and 2006. On effort transect lines are depicted for each survey, along with the 1500-m isobath in light gray.